Asymmetric Planetary Nebulae III
ASP Conference Series, Vol. XXX, 2004
M. Meixner, J. Kastner, B. Balick and N. Soker eds.

Stellar Rotation and the Formation of Asymmetric Nebulae

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Abstract. We illustrate how rotation of the central star can give rise to latitudinal variations in the wind properties from the star. Interaction of these winds with the surrounding medium can produce asymmetrical planetary nebulae.

1. Introduction

Planetary Nebulae (PNe) exhibit a dazzling variety of shapes, as emphasized so effectively in various talks at this conference. While this diversity does not allow easy classification, it is universally accepted that most, if not all, PNe do not show spherical symmetry. Balick (1987) classified them as ranging from spherical through elliptical to bipolar, which show two lobes emanating from an equatorial waist. The origin of this asymmetry in shape has been the cause of much speculation. A favored model for many years was the Generalized Interacting Stellar Winds Model (GISW; see Frank 1999 and references therein), which stated that the asymmetry was due to the expansion of the nebula within a structured ambient medium, whose density was higher at the equator than at the poles. The high equatorial density inhibits the expansion at the equator, leading to a prolate or, for very high density contrasts, a bipolar nebula.

While many authors have shown (eg. Dwarkadas, Chevalier & Blondin 1996) that this model can reproduce a vast diversity of morphologies, it does not seem to reproduce many of the details. Besides, the nagging question of what produces the asymmetry in the surrounding medium has always persisted. Rotation, binary evolution, magnetic fields, pre-existing disks, stellar pulsations and many other suggestions have been put forward, none of them ubiquitous or totally convincing. Many authors have also questioned whether it is likely that such an asymmetric density distribution is really present in every aspherical planetary nebula, given the lack of visible evidence.

In this work we show that rotation of the central star can lead to aspherical mass-loss from the star. This aspherical wind expanding into a constant density medium forms an aspherical nebula, without having to resort to any external asymmetries. Our results, although derived primarily from radiatively driven wind-theory applied to high luminosity stars (see Dwarkadas & Owocki 2002 for further details), have more general applicability, and could prove relevant for the central stars of PNe.

2. Effect of Rotation

For a rotating star, reduction by the radial component of the centrifugal acceleration yields an effective gravity that scales with co-latitude θ as

$$g_{eff}(\theta) = g\left[1 - \kappa_e F/gc - \Omega^2 \sin^2\theta\right], \tag{1}$$

where $\Omega \equiv \omega/\omega_c$, with ω the star's angular rotation frequency, and $\omega_c \equiv \sqrt{g/R}$, F is the stellar radiative flux and κ_e is the electron scattering opacity.

For a broad range of stellar wind-driving mechanisms, flow terminal speed scales directly with the surface escape speed. If the star is uniformly bright, then the latitudinal variation of terminal speed goes as:

$$\frac{v_\infty(\theta)}{v_\infty(0)} = \left[\frac{g_{eff}(\theta)}{g_{eff}(0)}\right]^{1/2} = \left[1 - \frac{\Omega^2 \sin^2\theta}{1-\Gamma}\right]^{1/2}, \tag{2}$$

where the polar speed $v_\infty(0) \sim \sqrt{gR(1-\Gamma)}$, and Γ = Eddington parameter.

However, if $F(\theta) \propto g(1 - \Omega^2 \sin^2\theta)$ (gravity darkening effect, von Zeipel, 1924) then this implies

$$\frac{v_\infty(\theta)}{v_\infty(0)} = \left[\frac{g_{eff}(\theta)}{g_{eff}(0)}\right]^{1/2} = \left[1 - \Omega^2 \sin^2\theta\right]^{1/2}. \tag{3}$$

The evolution of the wind velocity is quite general, and does not depend strongly on the details of the wind-driving mechanism. This is not true for the mass-loss rate. In order to determine the mass-loss rate, we must include more details of the specific wind-driving mechanism. We derive our results from radiatively-driven wind theory (see Owocki et al. 1998; Dwarkadas & Owocki 2002), applicable mainly to PNe with hot O and WR type central stars.

For a star with luminosity L, the CAK, line-driven mass loss rate (Castor, Abbott & Klein 1975) can be written in terms of the mass flux $\dot{m} \equiv \dot{M}/4\pi R^2$ at the stellar surface radius R, which then depends on the surface radiative flux $F = L/4\pi R^2$ and the effective surface gravity $g_{eff} \equiv (GM/R^2)(1-\Gamma)$ through (Owocki, Cranmer & Gayley 1998; Dwarkadas & Owocki 2002)

$$\dot{m} \propto F^{1/\alpha}\, g_{eff}^{1-1/\alpha}. \tag{4}$$

where $\alpha < 1$. If the radiative flux F is constant over the stellar surface, then $\kappa_e F/gc = \Gamma$ in equation (1), and application of equation (4) yields

$$\frac{\dot{m}(\theta)}{\dot{m}(0)} = \left[\frac{g_{eff}(\theta)}{g_{eff}(0)}\right]^{1-1/\alpha} = \left[1 - \frac{\Omega^2 \sin^2\theta}{1-\Gamma}\right]^{1-1/\alpha}. \tag{5}$$

Since the exponent $1 - 1/\alpha$ is negative, the mass flux from such a uniformly bright, rotating star increases from the pole ($\theta = 0$) to the equator ($\theta = 90$).

However, taking gravity darkening into account yields the mass flux scaling:

$$\frac{\dot{m}(\theta)}{\dot{m}(0)} = \frac{F(\theta)}{F(0)} = 1 - \Omega^2 \sin^2\theta \tag{6}$$

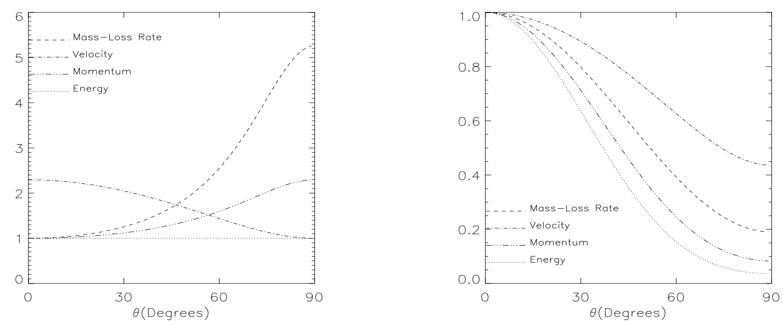

Figure 1. The variation of the wind velocity, mass-loss rate, momentum and energy with co-latitude, for the case of rotation with (right) and without (left) gravity darkening, using α=0.5. $\theta = 0$ refers to pole.

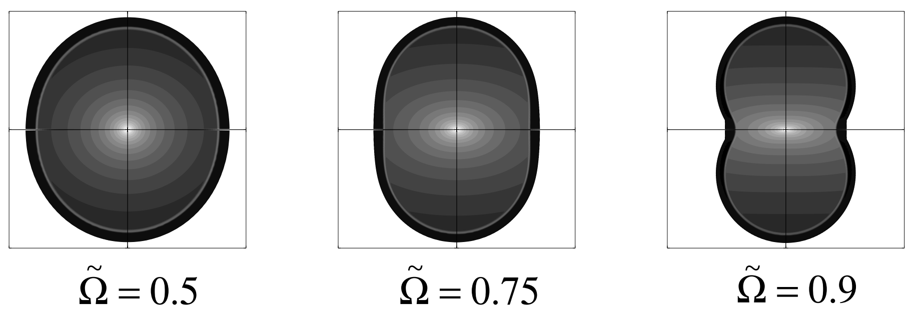

Figure 2. Density contours from simulations of an aspherical wind from a rotating star expanding in a constant-density medium.

i.e. the mass flux is highest at the poles, and decreases towards the equator.

Rotation thus generates a wind that is faster at the poles, but denser at the equator. The inclusion of gravity darkening leads to a wind that is both faster and denser at the poles than the equator. These effects are illustrated in Fig 1.

Figure 2 shows results from simulations for values of the rotation parameter $\tilde{\Omega} = \Omega/(1 - \Gamma)$, without including gravity darkening. The nebula is still in the early stages of evolution, and there is no hot, high-pressure bubble driving the expansion. As the rotation parameter increases from 50% to 90% of critical, the nebular morphology changes from nearly spherical to distinctly bipolar.

Inclusion of gravity darkening alters only the interior density distribution, and not the overall morphology. This indicates that it is the wind velocity distribution that is primarily responsible for shaping the nebula.

3. Conclusions and Discussion

We have shown that rotation can significantly modulate the winds from stars, leading to higher velocities and larger wind-momentum at the poles as compared to the equator. This can drive an aspherical, and even bipolar wind-blown

nebula, without having to resort to any external, ad-hoc density asymmetry. The nebula will start out as a momentum-driven, aspherical, structure, whose morphology depends on the rate of rotation. Over time it will slowly *lose* its asphericity, becoming more and more spherical as it evolves into an energy-conserving bubble. This situation is inverse to that of the GISW model, where the nebula slowly becomes more aspherical over time.

The results derived herein for the mass-flux are obtained using radiatively-driven wind theory from hot, luminous stars. However we emphasize that the shaping of the nebula depends mainly on the asymmetry in velocity, which is not strongly dependent on the specific wind-driving mechanism. A star rotating at a large fraction of critical velocity will be flattened, resulting in a faster wind at the poles than the equator, producing an elliptical or bipolar nebula.

The question remains then whether such large rotation velocities are typical of PNe central stars. AGB stars in general are known to be slow rotators. However we also know of exceptions such as V Hydra (Barnbaum et al. 1995), which is claimed to be rotating at close to critical velocity. Dorfi and Hoefner (1996) have shown that even small rotational velocities (of the order of 2 km/s) at the stellar photosphere can cause significant variations in the outflow velocities and mass-loss rate. The variations that they find in their models look similar to those in our models, although they are computed for dust-driven winds.

The presence of a binary companion can lead to increased rotation rates. Common envelope binary evolution, the presence of planets around stars and tidal spin-up by a binary companion all tend to increase the rotation velocities of stars. Many authors (see Bond 2000) have found that a large percentage of PNe central stars may exist in binary systems. In view of the theoretical possibility, as well as presently available observational evidence (however slim), we feel that fast rotation of PNe central stars cannot be ruled out.

Acknowledgments. Vikram Dwarkadas is supported by Award # AST-0319261 from the National Science Foundation, and by the US. Dept. of Energy grant # B341495 to the ASCI Flash Center (U Chicago). Collaboration with Dr. Stan Owocki on this research is gratefully acknowledged. A big thanks to the organisers for inviting me to an engrossing conference in a fascinating setting.

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